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Original article

Assessment of the function and resistance of sternoclavicular ligaments: A biomechanical study in cadavers

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ABSTRACT

Background: Few biomechanical studies have assessed the resistance of the ligamentous structures of the sternoclavicular joint, and none have reproduced the physiological movements of the joint. Determining the structures that are injured in sternoclavicular dislocations is important for the surgical planning of acute or chronic ligament reconstruction.

Methods: Forty-eight joints from 24 human cadavers were studied, and they were divided into 4 groups of 12 joints each (retraction, protraction, depression and elevation). Biomechanical testing assessed primary and secondary failures. The mechanical resistance parameters between movements that occurred on the same plane (depression versus elevation, protraction versus retraction) were compared.

Results: The posterior sternoclavicular ligament was the most injured structure during the protraction test, but it was not injured during retraction. The anterior sternoclavicular ligament was the most affected structure during retraction and depression. The costoclavicular ligament was the most affected structure during elevation. Joint resistance was significantly greater during protraction movements when compared to retraction ($P < 0.05$).

Conclusion: The anterior sternoclavicular ligament was the most affected structure during retraction and depression movements. During protraction, lesions of the posterior sternoclavicular ligament were most frequent during elevation, and the costoclavicular ligament was the most frequently injured ligament. The resistance of the sternoclavicular joint was significantly greater during protraction movement when compared to retraction.

Level of evidence: IV, basic science, biomechanics, cadaver model.

1. Introduction

The sternoclavicular joint (SCJ) is the only true joint joining the upper limbs to the axial skeleton [1]. It is the least constricted joint in the human body, and its stability depends on ligament structures [1]. The SCJ can be affected by instability, and although it represents only 3% of the dislocations of the shoulder girdle [2,3], there is a potential risk of dysfunction and eventually death [4].

Few biomechanical studies have assessed the resistance of SCJ ligament structures [5,6], and no studies have reproduced the physiological movements of the joint. There are several ligament reconstruction techniques [7–11], but no gold standard has been defined [12–14]. Determining the structures injured in sternoclavicular dislocations is important for the surgical planning of acute or chronic ligament reconstruction.

The present study primarily aimed to describe the first anatomical structures injured at the limits of depression, elevation, protraction and retraction movements of the SCJ. The secondary objectives were to evaluate the sequence of lesions occurring after primary failure and to quantify and compare the resistance of the sternoclavicular joint in different movements, through biomechanical testing using a cadaver model.

2. Materials and methods

Forty-eight SCJs were obtained from 24 fresh cadavers. All of the specimens originated from adult cadavers with no history of thoracic trauma or previous SCJ disorders. The specimens consisted of the sternum (cross-sectioned between the 6th and 7th costal cartilage), the 1st rib (sectioned at its tubercle), the proximal portions

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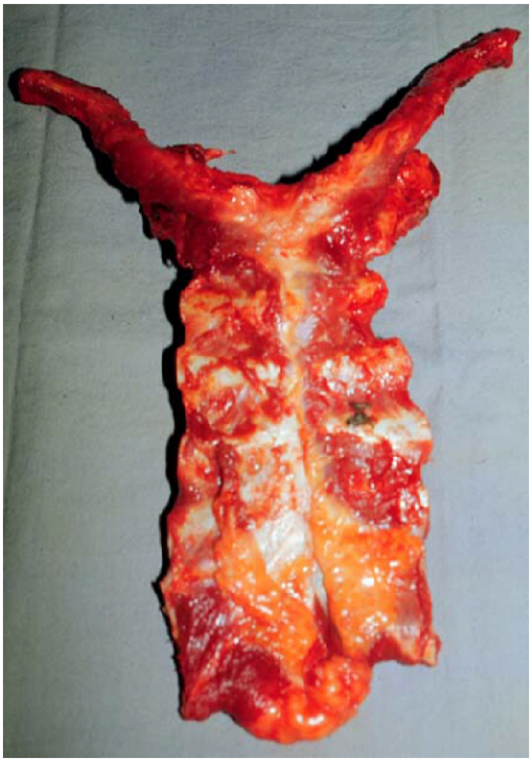

Fig. 1. Anatomical specimen removed from a cadaver.

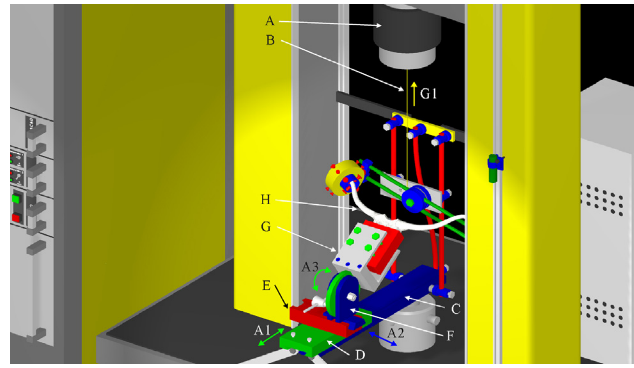

Fig. 3. Schematic representation of the mechanical device for torsion testing of the sternoclavicular joint, attached to a mechanical testing machine. (A. Load cell of 5 tonne-force attached to the mobile plate of the mechanical testing machine. B. Steel cable. C. Horizontal rail. D. Longitudinal carriage. E. Transverse rail. F. Transverse carriage. G. Rectangular claw. H. Anatomical specimen fixed with acrylic cement. G1. Degree of linear freedom of the load cell of the testing machine. A1. Movement for the linear adjustment of the longitudinal carriage. A2. Movement for the linear adjustment of the transverse carriage. A3. Movement for the rotational adjustment of the rectangular claw).

of the 2nd, 3rd and 4th costal cartilage and the clavicle. The SCJ's integrity was preserved (Fig. 1).

The specimens were frozen and kept at −15 °C until the day of the tests. On the day of the mechanical tests, the specimens were thawed and brought to room temperature. They were then immersed in a 0.9% sodium chloride solution. At this time, all of the adjacent muscle was removed, and thus the joint capsule and the sternoclavicular, interclavicular and costoclavicular ligaments were well defined bilaterally (Fig. 2).

The sternal portions of the anatomical specimens were placed in a 500-mL plastic bag filled with polymethylmethacrylate. The manubrium was positioned parallel to the anterior face of the bag, so both the sternoclavicular joints and the superior portion of the manubrium projected above the cement block, allowing for free movement of the clavicle. The bag containing the specimen was covered with polymethylmethacrylate and was then attached by screws to a rectangular claw (Fig. 3G), making it possible to adjust its angle (Fig. 3A3) according to the study group.

The distal end of the clavicle was inserted into the claw's cylindrical tube (Fig. 4F) and was attached with 8 screws after the movement (Fig. 3A5) of the adjustable arm (Fig. 4D), according to the length of each clavicle. Contact between the tube and the cylindrical claw (Fig. 4E) was made by spheres coupled to the ends of 8 screws, allowing for linear freedom in the axial direction of the tube (Fig. 4G4) and rotational freedom around its longitudinal axis (Fig. 4G3). The system that attached the cylindrical claw to the adjustable arm allowed clavicle rotation during the tested movements (Fig. 4A6 and G5).

The mechanical device made it possible to place the specimen in the desired position by adjusting the movements (Figs. 3 and 4A1 to A6). After proper positioning, the adjusting components were blocked to prevent further movement. During the testing, the device allowed for some degree of freedom (Figs. 3 and 4G1 to G5) such that the intrinsic movements of the sternoclavicular joint were not blocked.

The positioning of the specimen at the joint axis was initially based on the insertion region of the costoclavicular ligament in the clavicle, aligned with the pulley axis (Fig. 4C) through a threaded

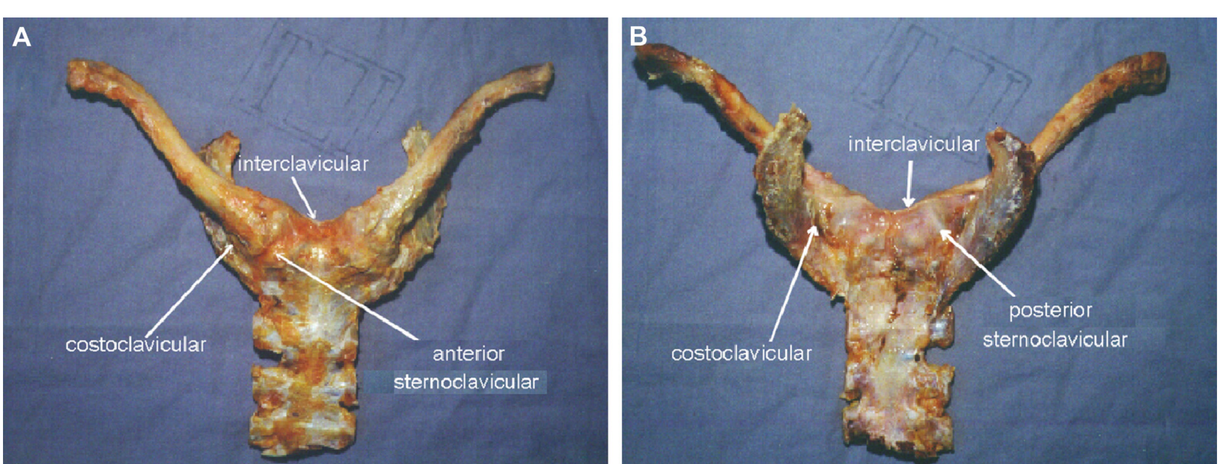

Fig. 2. Anatomical specimen after muscle resection, with indication of the costoclavicular, interclavicular, anterior and posterior sternoclavicular ligaments. A. Anterior view. B. Posterior view.

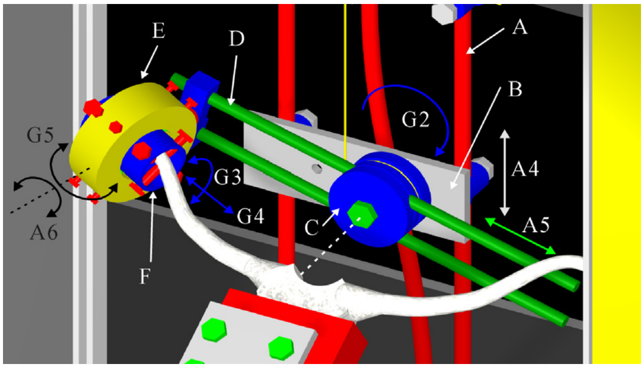

Fig. 4. Schematic representation of the anatomical specimen attached to the testing machine by a mechanical device for torsion testing of the sternoclavicular joint (A. Vertical rail. B. Vertical carriage. C. Pulley. D. Adjustable arm. E. Cylindrical claw. F. Cylindrical claw tube. G2. Degree of rotational freedom of the pulley. G3. Degree of rotational freedom of the cylindrical claw tube. G4. Degree of linear freedom of the cylindrical claw tube. G5. Degree of rotational freedom of the cylindrical claw with regard to the intersection plane of the adjustable arm. A4. Movement for the linear adjustment of the vertical carriage. A5. Movement for the linear adjustment of the adjustable arm. A6. Movement for the rotational adjustment of the cylindrical claw at the axis perpendicular to the intersection plane of the adjustable arm).

rod attached at its center. To that end, adjustments were performed (Fig. 3A1 and A2) of the longitudinal (Fig. 3D), transversal (Fig. 3F) and vertical (Fig. 4B) carriages in their own rails (Fig. 3C and E and Fig. 4A).

To perform the torsion testing, one of the ends of the steel cable (Fig. 4B) was attached to and surrounded by the pulley tube, and the other end was attached to a load cell (Fig. 4A). The inferior-to-superior movement of the load cell (Fig. 4G1) caused the steel cable to transmit rotation movement to the pulley, of which the adjustable arm moved the acromial end of the clavicle.

The failure load amount was determined by pilot tests before the experiment specimens were tested, in order to select the load cell to be fitted to the testing machine. The biomechanical test was performed using a device with a 5000-kgf load cell. The device was adjusted for a 500-kfg scale and coupled to a computer equipped with a data acquisition system. The collected data were manipulated to generate a graph (Fig. 4), which was used to obtain data for further statistical analysis (Fig. 5).

The specimens were divided into 4 study groups. Each group consisted of 12 joints (6 left-side joints and 6 right-side joints) that were subjected to a continuous force from superior-to-inferior (depression), inferior-to-superior (elevation), posterior-to-anterior (protraction) or anterior-to-posterior (retraction) positions, depending on the group.

During the testing, it was possible to determine which was the first injured structure, which was identified as "primary failure", corresponding to the maximum resistance limit. In most of the tests, the continuation of the movement caused lesions in other structures, which were identified as "secondary failure".

The assessment criteria were based on the analysis of the injured structures, the frequencies of lesions and the sequence in which they occurred (primary and secondary failures). Quantitative parameters were obtained from the analysis of each test's graphs and the rigidity during the elastic phase; the torsional moment at the maximal resistance limit, the angular displacement at the maximal resistance limit, the torsional moment at the proportional limit and the angular displacement at the proportional limit were also determined. The proportional limit was determined employing the Johnson method modified by the variation proposed by Moore. We also compared the groups, the movements of which were performed on the same plane (depression versus elevation, protraction versus retraction).

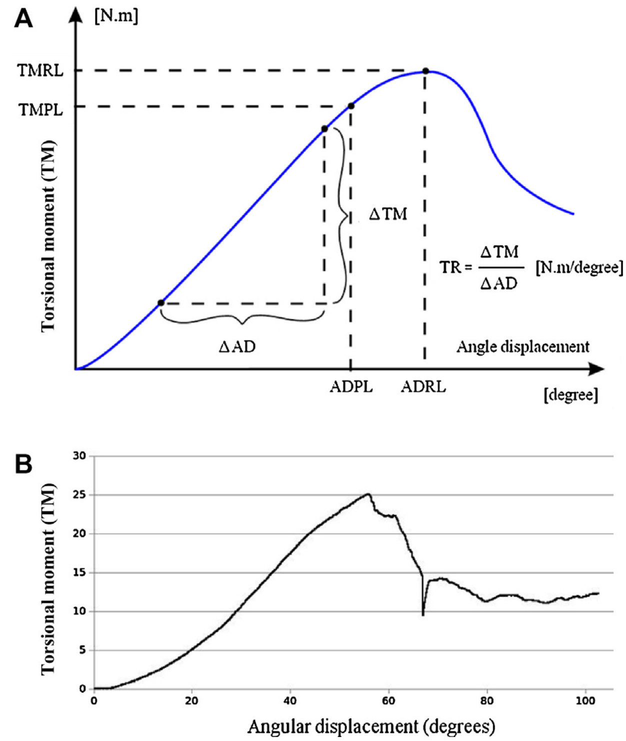

Fig. 5. Hypothetical graph of a sternoclavicular joint torsion test, showing the quantitative parameters analyzed. TMRL: torsional moment at the maximum resistance limit; TMPL: torsional moment at the proportional limit; ADRL: angular displacement at the maximum resistance limit; ADPL: angular displacement at the proportional limit; ΔTM: variation in the torsional moment between 2 points in the linear region; ΔAD: variation of angular displacement between 2 points in the linear region; TR: torsional rigidity.

3. Statistical analysis

The frequency (absolute and relative) of failure (primary and secondary) during the testing was assessed for each group. The relative frequency is expressed as percentages.

Descriptive statistics were performed and included means and standard deviations of the quantitative parameters of torsional rigidity, torsional moment at the maximal resistance limit, angular displacement at the resistance limit and torsional moment at the proportional limit.

The results from the groups, the movements of which occurred at the same plane, were compared (depression versus elevation and protraction versus retraction) using Mann-Whitney "U" test.

In all cases, a significance level of 5% ($P = 0.05$) was considered, and significant results are indicated with an asterisk.

4. Results

The depression movement of the clavicle caused, most frequently, primary failure of the anterior sternoclavicular ligament (75%) and secondary failure of the first rib (50%). During elevation, there was mainly primary failure of the costoclavicular ligament (58.3%) and secondary failure of the anterior sternoclavicular ligament (25%) and associated lesions of the anterior and posterior sternoclavicular ligaments (16.7%).

Movements performed on the axial plane did not result in an evident predominance of lesions of one structure over others. During protraction, primary failures of the posterior sternoclavicular ligament (41.7%) and the 1st rib (25%) and secondary failures of the costoclavicular ligament (33.3%) and the 1st rib (25%) were the most common in these cases. During retraction, primary failures

Table 1
Distribution of primary and secondary failures according to each group.

Primary failure	n	%	Secondary failure	n	%
Depression					
ASCL	9	75	FFR	6	50
CA	1	8.3	FFR/ICL	1	8.3
SA	1	8.3	ICL	1	8.3
MFC	1	8.3	PSCL	1	8.3
			None	3	25
Total	12	100	Total	12	100
Elevation					
CCL	7	58.3	ASCL	3	25
FFR	4	33.3	ASCL/PSCL	2	16.7
CCL/FFR	1	8.3	PSCL	1	8.3
			None	6	50
Total	12	100	Total	12	100
Protraction					
PSCL	5	41.7	CCL	4	33.3
FFR	3	25	FFR	3	25
PSCL/ICL	1	8.3	PSCL	2	16.7
CA	1	8.3	ICL	1	8.3
PSCL/CCL	1	8.3	None	2	16.7
Total	12	100	Total	12	100
Retraction					
FFR	4	33.3	ASCL	3	25
ASCL	4	33.3	CCL	2	16.7
CCL	4	33.3	FS	1	8.3
			FFR	1	8.3
			None	5	41.7
Total	12	100	Total	12	100

ASCL: anterior sternoclavicular ligament; CA: clavicle avulsion; SA: sternum avulsion; MFC: metaphyseal fracture of the clavicle; FFR: fracture of the first rib; CCL: costoclavicular ligament; PSCL: posterior sternoclavicular ligament; ICL: interclavicular ligament; FS: fracture of the sternum.

of the 1st rib, anterior sternoclavicular ligament and costoclavicular ligament showed the same incidence (33.3%), while the most frequent secondary failures were of the anterior sternoclavicular ligament (25%) and costoclavicular ligament (16.7%).

Detailed distributions of primary and secondary failures per group are shown in Table 1.

We observed articular disc lesions in 34 specimens. In 22, a lesion occurred between the articular disc and clavicle, in the other between sternum and the articular disc.

Distribution according to study group, with regard to torsional rigidity, torsional moment at the maximal resistance limit, angular displacement at the maximal resistance limit, torsional moment at the proportional limit and angular displacement at the proportional limit are provided in detail in Table 2.

The comparative analysis of the movements performed on the same plane showed that depression and protraction exhibited significantly higher results than elevation and retraction, respectively, with regard to torsional rigidity, torsional moment at the maximal resistance limit and torsional moment at the proportional limit (Table 2).

5. Discussion

Few biomechanical studies can be found in the literature on the assessment of the resistance of SCJ ligaments. The present study is pioneering in the evaluation of injured structures according to the 4 basic movements of this joint and the force necessary to cause these failures.

In 1967, Bearn [5] conducted the first biomechanical analysis of the SCJ. In that study, the author noted that sectioning of the joint capsule resulted in instability. However, the only deforming force employed was depression of the lateral portion of the clavicle, without applying deforming forces on the horizontal plane; that is, the most common movements (protraction and retraction) were not considered. Furthermore, the author performed complete sectioning of the joint capsule, without distinguishing the different ligaments, and there was no quantitative assessment of ligament resistance. Thus, the practical application of the study was limited.

Spencer et al. [6], in 2002, performed a study aimed at determining the importance of the different SCJ ligaments during anterior and posterior translational movements. They subjected the SCJ to a submaximal load, previously determined in a pilot study, and they randomly injured the ligament structures. The authors observed that the posterior capsule was the most important structure in restraining both anterior and posterior translation. The anterior capsule was a secondary aid against anterior translation, while the costoclavicular and interclavicular ligaments did not exhibit an important role in the studied movements.

Unlike the study by Spencer et al. [6], in which the load was applied up to a submaximal force and in which the ligament lesion was caused in a directed and individual manner, the present study measured the necessary force to cause primary and secondary lesions. We believe that the deforming force used in our study imitates more adequately what happens in real situations, including the observation of associated injured structures in some situations. Moreover, the methods used included physiological movements of the SCJ (depression, elevation, protraction and retraction), while the authors of the previous study used pure translational movements.

In the present study, the posterior sternoclavicular ligament, considered the main restrictor of anterior and posterior translation [6], displayed lesions in 57.8% of the cases during protraction (41.7% as primary failures and 16.7% and as secondary failures) and remained intact in 42.2% of cases. This ligament was not injured during retraction movement. The anterior sternoclavicular ligament, considered the secondary restrictor of anterior translation [6], was the primary injured ligament in the present study during retraction, occurring in 58.3% of cases (33.3% as primary failures and 25% as secondary failures) and also during depression (75% of primary failures). The costoclavicular ligament, in turn, was the most affected structure during elevation (58.3% of primary failures).

When analyzing the force needed to cause primary and secondary failures, it was found that the rigidity in the elastic phase,

Table 2
Resistance measurements during different movements of the sternoclavicular joint.

	Depression	Elevation	p 1	Protraction	Retraction	p 2
Rigidity	445.83 ± 120.81	319.89 ± 92.91	0.0121*	460.61 ± 138.20	331.24 ± 78.00	0.0073*
TMRL	20.10 ± 7.38	13.21 ± 5.91	0.0242*	18.04 ± 7.53	12.25 ± 3.53	0.0387*
ADRL	63.28 ± 15.12	62.96 ± 12.61	0.977	59.35 ± 19.03	56.54 ± 18.89	0.5834
TMPL	17.04 ± 6.41	10.90 ± 5.67	0.0242*	14.19 ± 6.46	10.80 ± 3.71	0.0396*
ADPL	49.08 ± 8.72	46.90 ± 12.40	0.977	43.61 ± 15.95	44.42 ± 11.58	0.8852

Rigidity: rigidity during elastic phase in Nm.10^{-3}/degree; TMRL: torsional moment (torque) at the maximum resistance limit in Nm; ADRL: angular displacement at the maximum resistance limit in degrees; TMPL: torsional moment (torque) at the proportional limit in Nm; ADPL: angular displacement at the proportional limit in degrees; *p* 1: comparison between depression and elevation; *p* 2: comparison between protraction and retraction; * $P < 0.05$.

the torsional moment at the maximal resistance limit and the torsional moment at the proportional limit were significantly higher during protraction when compared to retraction, which agrees with the most frequent dislocation of the SCJ being anterior dislocation [15].

We believe that knowledge about which structures are injured in each of the movements of the SCJ and data on the resistance of ligament structures could be useful in clinical practice, facilitating surgical planning and the development of techniques for repair and reconstruction.

Reconstruction of the unstable SCJ can be achieved by different techniques, with satisfactory clinical outcomes described in case reports. However, the ligaments reconstructed vary between these techniques and some authors perform only the anterior sternoclavicular ligaments. Spencer and Kuhn [16] demonstrated the reconstruction of both ligaments, with a figure-of-8 technique, is biomechanically superior and may result in improved long-term outcomes. Our paper demonstrated that both anterior and posterior sternoclavicular ligaments are frequently injured during SCJ dislocation and reconstruction of both ligaments could achieve more anatomical results.

It is noteworthy that in the present study, the outcomes analyzed during the experiment were primary and secondary failures, and the deforming force was not maintained until dislocation. This is a possible explanation for the relatively low occurrence of posterior sternoclavicular ligament lesions.

The device used in the present study applied only continuous non-cyclical loads. However, as the study aimed to determine the injured structures for each of the deforming forces, we believe that this fact does not constitute a limitation. Assays with cyclical loads would be needed when comparing the resistance of repair and reconstruction techniques with the resistance of native capsuloligamentous structures.

The present study is limited by it having been a test with cadavers, and the evaluation of the primary outcome refers to the 4 basic movements alone, the results of which are not necessarily reproducible in the mechanism of trauma of SCJ dislocation. Moreover, muscle function was not considered — only ligament function. But, SCJ main stabilisers include strong extrinsic and intrinsic ligaments and to a lesser extent a dynamic muscular [17].

6. Conclusion

The most prevalent primary failures were those of the anterior sternoclavicular ligament during depression, the costoclavicular ligament during elevation, the posterior sternoclavicular ligament during protraction and the anterior sternoclavicular, costoclavicular ligaments and the 1st rib during retraction. Secondary failures were most prevalent for the 1st rib during depression, the anterior sternoclavicular ligament during elevation and retraction and the costoclavicular ligament during protraction. Joint resistance was significantly higher during protraction movement when compared to retraction and during depression when compared to elevation.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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